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Abstract. A seismic hazard map proposed as part of a new building code for Romania is presented here on basis of the recommendations in EUROCODE 8.

Seismic source zones within an area of about 200 km around Romania were constructed considering seismicity, neotectonics and geological development. The probabilistic seismic hazard assessment in terms of intensities is performed following Cornell (1968) with the program EQRISK (see Mc Guire, 1976), modified by us for use of intensities.

To cope with the irregular isoseismals of the Vrancea intermediate depth earthquakes a factor Ω is introduced to the attenuation law (Kövesligethy, 1907). Using detailed macroseismic maps of three earthquakes Ω is calculated by fitting the attenuation law to observed intensities, i.e. to local ground conditions. Strong local variation of Ω is avoided by a gridding of 0.5° in longitude and 0.25° in latitude. The contribution of the Vrancea intermediate depth zone to the seismic hazard at each grid point is computed with the corresponding representative Ω. A seismogenic depth of 120 km is assumed.

The final seismic hazard is the combination of both contributions, of zones with crustal earthquakes and of the Vrancea intermediate depth earthquakes zone. Calculations are done for a recurrence period of 95, 475 and 10 000 years. All maps show the dominating effects of the intermediate depth earthquakes in the Vrancea zone, also for the capital Bucharest.

1 Introduction

In Romania there are several significant areas of seismicity (Fig. 1) with earthquakes at normal depths (less than 60 km) as well as intermediate depth (60–180 km). The most active zones are in the western part of Romania near the city of Timisoara (BA, DA), in the central part near Sibiu (FC) and in the north western part at Baia Mare (CM). Romania's high level of seismic hazard is mostly governed by events of the Vrancea region at the Eastern Carpathian arc bend.

To our knowledge the present study is the first seismic hazard assessment in terms of macroseismic intensities for Romania. Probabilistic seismic hazard maps in terms of horizontal peak ground acceleration were published by Musson (2000), Mäntyniemi et al. (2003) and Marmureanu et al. (2004). Musson (2000) presented maps for the Pannonian Basin (including Romania) for return periods of 100, 475, 1000 and 3000 years. For earthquakes in the intermediate depth Vrancea seismic zone he used three different attenuation models depending on the direction from the source. Mäntyniemi et al. (2003) mapped for a return period of 475 years the specific seismic hazard for the Vrancea seismic zone using depth- and azimuth-dependent attenuation functions. On the other hand Marmureanu et al. (2004) solely investigated the seismic hazard from crustal earthquakes. A deterministic approach was used by Radulian et al. (2000) by computing synthetic seismograms.

A seismic hazard map proposed as part of a new building code of Romania based on EUROCODE 8 (EC 8) is presented here in terms of macroseismic intensities. As recommended in EC 8 two maps are calculated: for a probability of exceedance of 10% in 50 years (recurrence period of 475 years) and a probability of exceedance of 10% in 10 years (recurrence period of 95 years).

2 Probabilistic Seismic Hazard Assessment (PSHA) and treatment of the crustal earthquake zones

Basis of the probabilistic analysis is the earthquake catalogue for SE-Europe (Shebalin et al., 1998). Epicenters and

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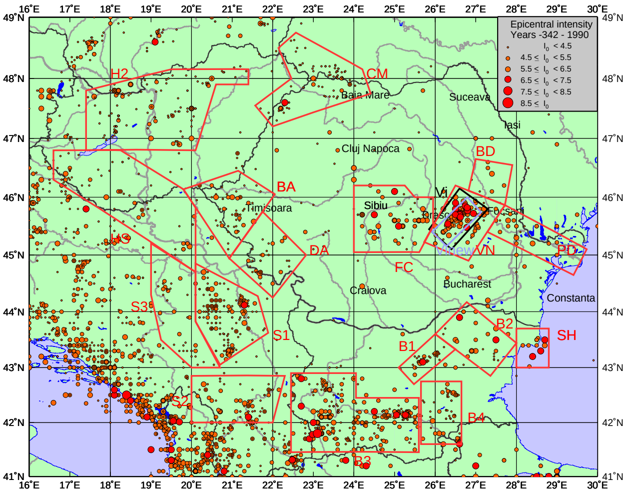

Fig. 1. Epicenter map (Shebalin et al., 1998) with the seismic source zones. Codes refer to Table 1.

seismic source zones in an area of about 200 km around the territory of Romania are shown in Fig. 1. The boundaries of these zones were chosen to reflect the seismicity adequately regarding tectonic units and lithospheric structure as well as the suggested zonations given by Musson (2000), Radulian et al. (2000), Bala et al. (2003) and Marmureanu et al. (2004).

As a Poisson distribution is assumed earthquakes have to be independent events. In case of more than one earthquake within 10 days and 50 km distance only the strongest event is used for the statistics; the others are declared as statistical dependent (pre- and aftershocks) and eliminated from the catalogue. The beginning of the time period for statistical purposes is chosen according to the assumed completeness of the catalogue for events greater than the lowest intensity value used in statistics. The intensity frequency parameters a and b for each zone (Table 1) are calculated with Eq. (1).

$$\log N(I) = a + bI_{\text{epic.}} \tag{1}$$

$N(I)$ is the cumulative number of earthquakes; $I_{\text{epic.}}$ is the epic. intensity.

The maximum credible earthquake for each zone is estimated (Table 1) with respect to seismicity, frequency of earthquakes, maximum observed intensity and quality of historical documents.

Some seismic regions display few and disperse seismicity. They are treated in a special way (see Table 1) to calculate the intensity frequency statistic. All earthquakes excluding those of the designed sources are assigned to the ”background seismicity”. The seismogenic depth of a region is defined where maximum of energy is released.

The seismicity within the Vrancea region consists of two depth horizons: normal deep (less than 60 km) and intermediate deep (60–180 km) events. Due to extremely irregular isoseismals of the intermediate depth earthquakes their effects on the seismic hazard have to be treated separately.

The probabilistic seismic hazard for Romania is computed with EQRISK developed by McGuire (1976). It is based

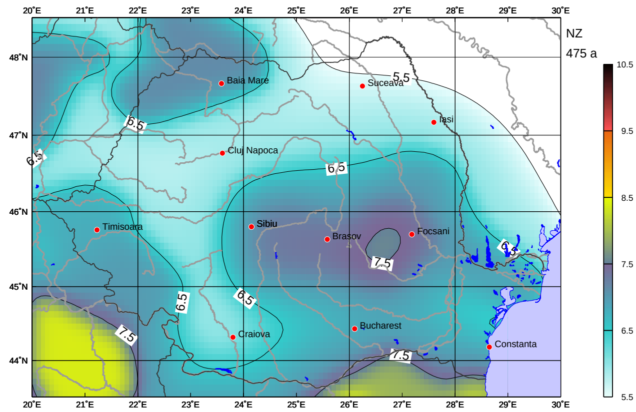

Fig. 2. Seismic hazard from source zones of normal depth for a recurrence period of 475 years; colours represent the intensities in MSK.

on the probabilistic approach of Cornell (1968). We implemented the intensity attenuation function of Sponheuer (1960) based on Kövesligethy (1907).

$$I_{\text{site}} = I_{\text{epic.}} - 3\log(r/h) - 1.3\alpha * (r - h) \tag{2}$$

r is the hypocentral distance (km); h is the depth (km); and α is the absorption coefficient, here 0.002 km^{-1}.

For a hazard curve at a site EQRISK cuts all source regions into finite ring segments with their statistical parameters. Then the site intensities caused by earthquakes of each segment are calculated assuming a standard deviation of half an intensity. The sum of all contributions from all regions finally leads to the annual probability of exceedance at each grid point of the hazard map. These calculations are done for all points between 43.5° N to 48.5° N and 20.0° E to 30.0° E every 0.1° in latitude and 0.2° in longitude. Figure 2 shows the seismic hazard for Romania due to the earthquakes of normal depths only.

3 Vrancea intermediate depth earthquake zone

Macroseismic and early instrumental data have shown that the seismicity in the Vrancea zone is dominated by intermediate depth events located in a well defined volume. The epicentral area is confined to about 40×80 km. Most earthquakes occur at depths between 60 km and 180 km within an almost vertical column (e.g. Radu, 1974; Fuchs et al., 1979; Oncescu et al., 1999).

Shallower and deeper events were also recorded, however are less frequent and have only small to moderate magnitudes. Vrancea seismicity is further characterized by pronounced background activity which delineates the rupture area of the strong earthquakes (e.g. Oncescu and Bonjer, 1997).

During the last century four major earthquakes occurred: on 10 November 1940 (MW=7.7), 4 March 1977 (MW=7.4), 30 August 1986 (MW=7.1) and on 30 May 1990 (MW=6.9). During the 4 March 1977 event 1570 people died, 11 300

Table 1. Parameters of intensity-frequency relations and input-parameters for seismic hazard calculation. The a- and b-values are estimated using full intensity values. Half intensity values are added to the next higher intensity class. This enlarges the number of events in each class, which improves the statistical stability and is also more conservative.

Region	code	start year[1]	time interval	b value	a value	depth km	I_{max} observed	I_{max} credible
Banat N [2]	BA	1843	148	3.251	0.399	10	8.5	8.5
Birlad [3]	BD	1896	95	3.080	0.460	25	6.5	7
Background	BG	1817	174	3.949	0.453	10	8.5	8.5
Bulgaria N [4]	B1	1849	142	3.817	0.423	15	9.5	9.5
Bulgaria NE	B2	1832	159	3.705	0.416	15	9	9.25
Bulgaria S	B3	1818	173	5.237	0.520	12	10	10.25
Bulgaria SE [5]	B4	1893	98	4.063	0.520	10	8.5	9
Crisana Mamamures	CM	1781	210	5.130	0.573	10	8	8.5
Banat S [2]	DA	1864	127	3.200	0.399	12	8	8.5
Fagaras Campulung	FC	1517	474	3.467	0.374	20	8.5	9
Hungary Central	H2	1753	238	4.472	0.456	10	8.5	9
Hungary+Serbia	HS	1738	253	5.126	0.573	8	8.5	9
Predobroudja [3]	PD	1832	159	3.581	0.460	20	7.5	7.5
Shabla Zone [6]	SH	1901	90	3.157	0.416	15	10	10
Serbia E	S1	1886	105	4.891	0.487	10	9	9.5
Kosovo	S2	1897	94	4.678	0.529	10	8.5	9
Serbia W	S3	1894	97	6.081	0.803	10	7.5	8
Vrancea, normal depth	VN	1802	189	3.621	0.452	30	8	8.5
Vrancea, intermediate	Vi	1701	290	4.282	0.415	120	9	9.5

[1] End year for all regions is 1990; usually, only events with intensities of 5.5 or more are considered.
[2] For the two regions DA and BA, the events are added and a common intensity-frequency statistic is done, resulting in the same b-value. The a-value is computed: for region BA using the cumulative number of events with intensity 7.0 MSK and more; for region DA using the cumulative number of events with intensity 6.0 MSK and more.
[3] For the two regions BD and PD, the events are added and a common intensity-frequency statistic is done, resulting in the same b-value. The a-value for each region is computed, using the cumulative number of events with intensity 5.0 and more.
[4] The regression curve in the cumulative intensity-frequency relation for region B1 is calculated without the single event with intensity 9.5 MSK for statistical reasons; then the strongest event has an intensity of 8.0 MSK.
[5] For region B4 the b-value of B3 is taken. The a-value for region B4 is computed using the cumulative number of events with intensity 5.0 MSK and more.
[6] For region SH the b-value of B2 is taken. The a-value for region SH is computed using the cumulative number of events with intensity 6.0 MSK and more.

were injured and 32 500 residential and 763 industrial units were destroyed or seriously damaged, according to official data (e.g. Sandi, 2001).

With the deployment of modern seismic networks in the past decades, the accuracy of hypocenter locations increased considerably (e.g. Oncescu et al., 1999). In particular, Joint Hypocenter Determinations (JHD) showed that the Vrancea seismogenic zone has a two-dimensional geometry rather than a three-dimensional one (Oncescu, 1984; Oncescu and Trifu, 1987; Trifu et al., 1992; Oncescu and Bonjer, 1997). Recent analyses of the travel time data of the K2-network (Bonjer et al., 2000) reveal further details of the fine structure of the geometry of the Vrancea focal zone (Bonjer et al., 2005). The zone of seismic activity has a total width of about 20 km. It broadens from about 25 km at depths of 60 km to about 60 km at depths of 160 km. The earthquakes are located on two parallel planes (see blue and red circles in Figs. 3 and 4), separated by less than 10 km. The stars represent fore- and mainshock of 17 October 2005 sequence (Bonjer et al., 2005, Radulian et al., 2005).

To calculate the a- and b-value of Vrancea intermediate depth zone all epicenters inside $Vi_{\mathrm{stat.}}$ are used (Fig. 3). For the computation of seismic hazard the area of zone $Vi_{\mathrm{stat.}}$ was reduced to $Vi_{\mathrm{comp.}}$, according to the above well defined volume.

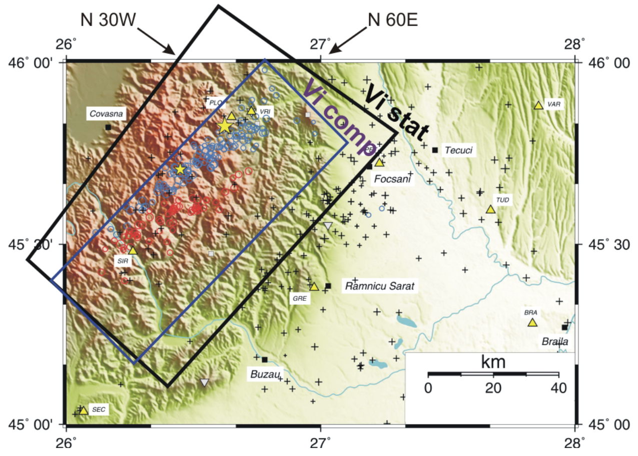

Fig. 3. JHD locations of the seismicity in the time period 1996–2003 at the South-Eastern Carpathian Arc bend (Bonjer et al., 2005). Blue and red circles: Vrancea intermediate depth earthquakes at two parallel active planes. Black crosses: crustal earthquakes. Large yellow star: epicenter of the event of 27 October 2004. Small yellow star: epicenter of the largest earthquake occurring in 2004 prior to 27 October (27 September, Mw=4.7). Triangles and squares: seismic stations. $Vi_{\text{stat.}}$ zone for statistics, $Vi_{\text{comp.}}$ zone for computation of seismic hazard.

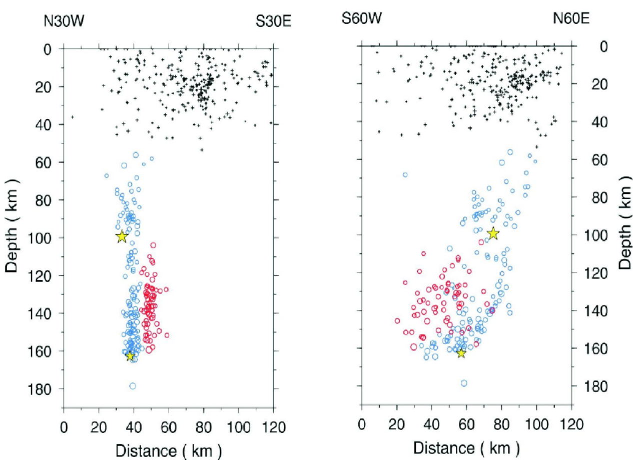

Fig. 4. Depth distribution of the earthquakes of Fig. 3 on two perpendicular, vertical cross sections in Vrancea area (for earthquakes between 1996 and 2003), striking N30W and N60E, respectively. Note the almost vertical plunge of the seismic activity on two parallel planes (left figure). Symbols and colours as in Fig. 3.

4 Treatment of Vrancea intermediate depth zone

Isoseismals of shallow earthquakes are almost circular shaped which is required to fulfil the assumed attenuation law of Sponheuer (1960). In contrast to them the isoseismals of earthquakes of intermediate depths are quite irregular shaped (Fig. 5). Observed intensities of the earthquakes of 4 March 1977 (Radu and Polonic, 1982), 30 August 1986 (Radu, personal communication) and 30 May 1990 (Radu and Utale, 1990) decrease in north western directions in

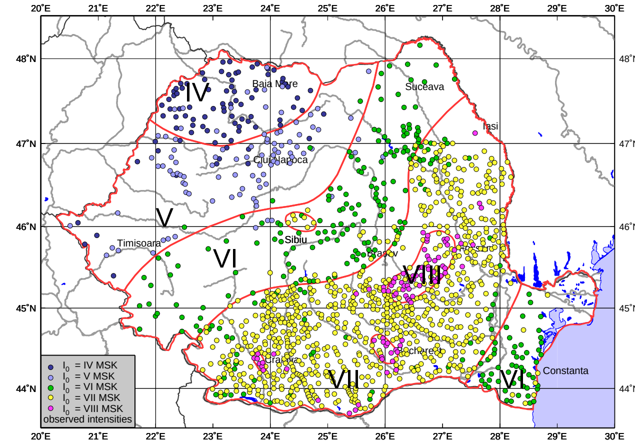

Fig. 5. Macroseismic field of the earthquake from 4 March 1977 (Radu and Polonic, 1982) with epicentral intensity I_0=VIII-IX MSK and h=94 km.

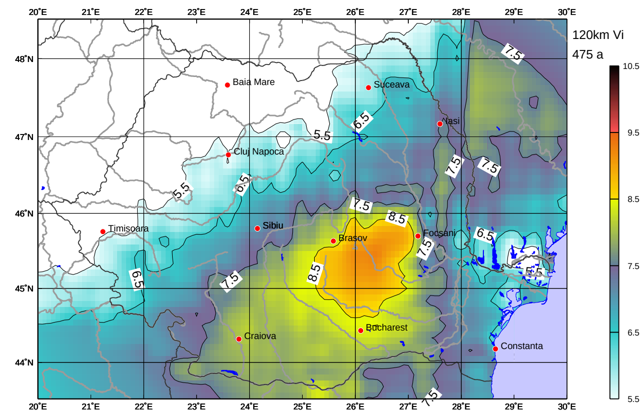

Fig. 6. Seismic hazard from Vrancea events of intermediate depth for a recurrence period of 475 years; colours represent intensities in MSK.

shorter distances than in north eastern and south western directions. Teleseismic tomography detected lower seismic velocities about 100 km northwest of Vrancea in an intermediate depth range of 70–110 km (Martin et al., 2004[1]). However, the phenomenon of the irregular shape of isoseismals of Vrancea intermediate depth earthquakes is still not explained.

As the attenuation law does not consider spatial differences in damping, a new empirical approach is chosen to take the directionality of attenuation into account. A factor Ω is introduced to the attenuation law in Eq. (2):

$$I_{\text{site}} = I_{\text{epic.}} - 3\log(r/h) - 1.3\alpha * \Omega(r-h) \quad (3)$$

Using detailed macroseismic maps of the three strong Vrancea intermediate depth earthquakes Ω is calculated

[1]Martin, M., Wenzel, F., and the CALIXTO Working Group: High resolution teleseismic body wave tomography for SE-Romania: Imaging of a slab detachment scenario, Geophys. J. Int., under review, 2004.

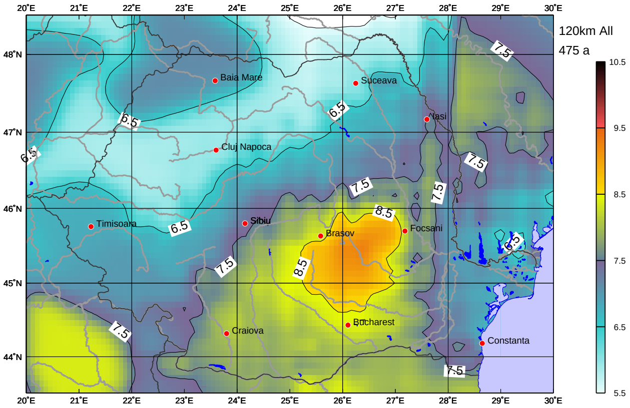

Fig. 7. Seismic hazard from all source zones for a recurrence period of 475 years; colours represent intensities in MSK.

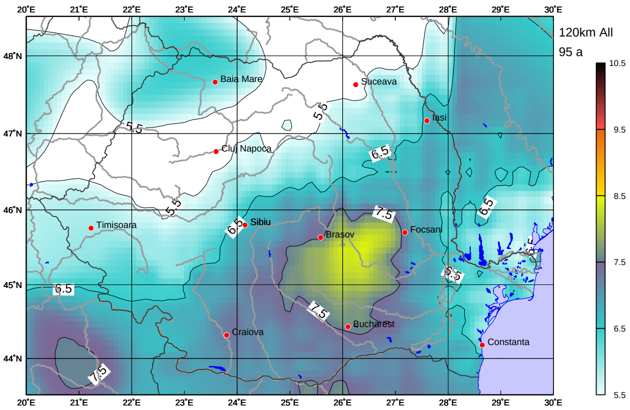

Fig. 8. Seismic hazard from all source zones for a recurrence period of 95 years; colours represent intensities in MSK.

for each observation. For simplification α is fixed to 0.001 km^{-1}. Strong local variations of Ω are avoided by calculation mean values inside grid cells of 0.56° in longitude and 0.25° in latitude, separately for each event. The median is taken to combine all three grids. Intensities for rectangles without observations have been 2D-interpolated respectively extrapolated.

Using the assigned Ω values for each point of observation, the seismic hazard of the Vrancea Intermediate Depth Zone (Vi) is calculated in the same way as for the crustal zones. A seismogenic depth of 120 km is assumed for Vi source zone. Figure 6 shows intensities for a recurrence period of 475 years.

5 Results

The final seismic hazard map for a recurrence period of 475 years in Fig. 7 is a combination of the map for source zones of normal depth (Fig. 2) and that for Vrancea intermediate depth zone (Fig. 6). Macroseismic observations for intermediate depth earthquakes are only available for Romania. Therefore our seismic hazard assessment is only valid for the Romanian territory.

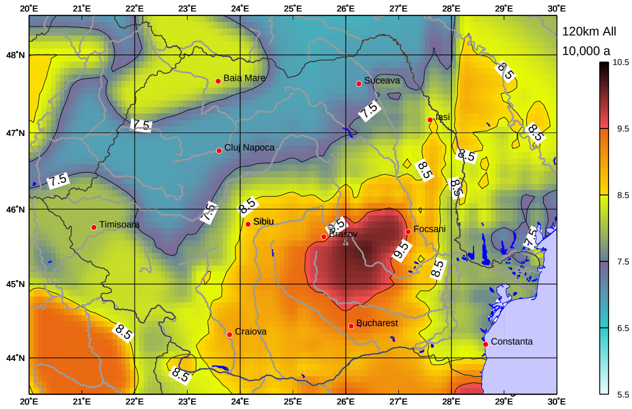

Fig. 9. Seismic hazard from all source zones for a recurrence period of 10 000 years; colours represent intensities in MSK.

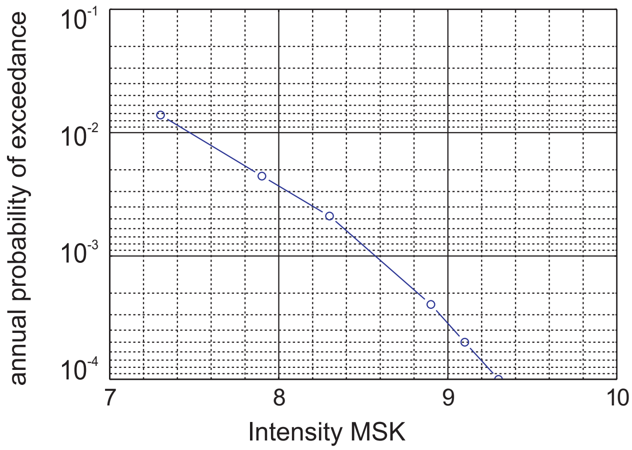

Fig. 10. Seismic hazard curve for Bucharest.

The intermediate depth earthquakes of the Vrancea Zone occur at depths of about 60 km to 180 km. To estimate the depths' influence, we calculated hazard maps for 95 km as well as for 150 km. The difference of the intensity values of both maps are in most cases less than half an intensity.

Recent building codes like the EC 8 recommend a recurrence period of 475 years (probability of exceedance of 10% in 50 years) for the design earthquake (Fig. 7). In EC 8 a second hazard level for a recurrence period of 95 years (probability of exceedance of 10% in 10 years) is recommended in addition, to limit the damage of buildings for weaker earthquakes with higher frequency of occurrence (Fig. 8). Special structures like nuclear power plants and large dams are beyond the scope of EC 8. For these structures higher safety standards, including longer recurrence periods, are required, e.g. 2475 years (2% in 50 years) for dams and 10 000 to 100 000 years for nuclear facilities. Figure 9 shows the seismic hazard for a recurrence period of 10 000 years in order to give decision makers first information for regional planning. This does not replace site specific expertises. A hazard curve for Bucharest is extracted from the hazard data set and shown in Fig. 10.

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